# *Ceramic Composite Development For Gas Turbine Engine Hot Section Components*

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# Introduction

- The development of ***monolithic ceramics*** for higher temperature hot-section components has been ongoing for about fifty years, but these materials have not been widely adopted due primarily to

  ***poor fracture toughness and resistance to damage***

  – In aggressive turbine environments
  – In interfacing with adjacent metallic components
  – In scale-up to large parts

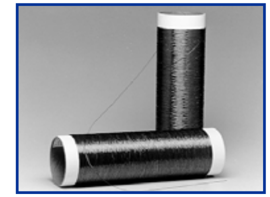
- Over the last decade, a variety of ***ceramic matrix composites*** (CMC) systems reinforced by continuous-length ceramic fibers have been developed that show performance benefits over monolithics for hot section components:
  – ***Higher tolerance to environmental and mechanical damage***
  – ***Net shape capability using conventional composite processes***
  – ***Greater size and volume capability without structural debit***

# *Objectives / Outline*

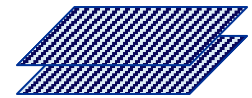
- Discuss the ***general property requirements*** for CMC to meet the design conditions for some advanced stationary and rotating CMC hot section components.
- Review briefly the current ***performance capabilities*** for some state-of–the-art ***oxide/oxide (Ox/Ox)*** and ***silicon-carbide/silicon-carbide (SiC/SiC) CMC*** material systems in meeting these requirements.
- Discuss current industry-wide issues regarding implementation of high-performance CMC in different hot-section components: ***environmental durability, shape producibility, design methodologies***, and ***affordability*****.**
- Briefly indicate some ***recent successes*** for CMC hot-section components.

# *Typical Fabrication Routes for CMC Components*

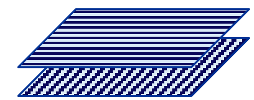
- Select **fiber** type in commercial tow form:



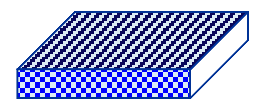
- Form 3D Component Shape by textile forming:
  - **2D Fabric Route :** Weave or braid tows into 2D fabric or cylindrical plies, and lay up plies into 3D architectures



  - **2D Prepreg Route**: Form unidirectional plies from straight tows, and lay up plies into 3D architectures



  - **3D Preform Route**: Weave or braid tows into 3D architectures with fibers thru-thickness for improved interlaminar properties

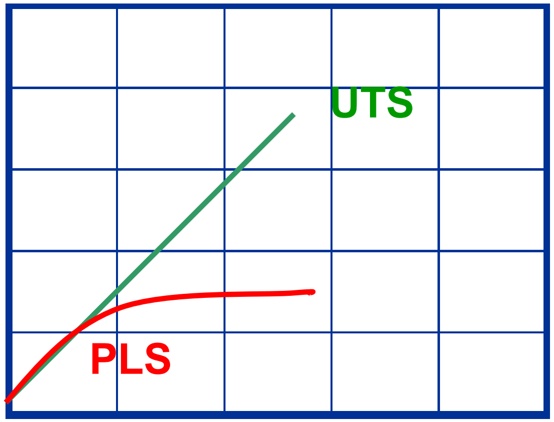


- For SiC/SiC, coat fibers in tow with thin BN-based **interphase** material using CVI (chemical vapor infiltration).
  - Typically no interphase coating is required for Ox/Ox due to highly porous matrix that provides crack deflection around fibers.
- Infiltrate 3D preform with various **matrix** materials using CVI gases and liquids such as polymers, slurries, and molten metals (Melt Infiltration) that convert to ceramics with different degrees of porosity.

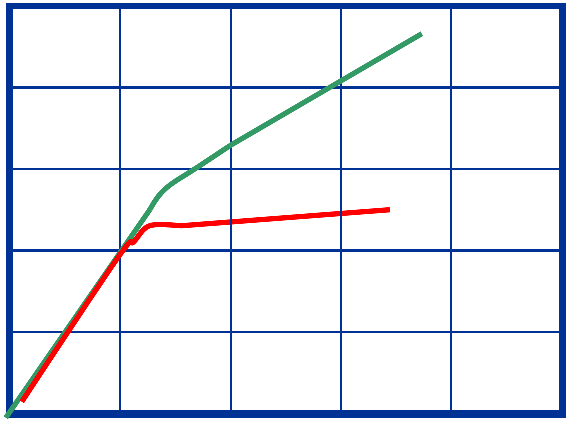
# Typical In-Plane Tensile Stress-Strain Behavior for Thin-Walled 0/90 2D CMC Panels

*Green = X or 0º Fiber Axis direction*    *Red = XY or 45/45 off-axis direction*

Porous Matrix




Dense Matrix



## General CMC Design Requirements <u>for all directions</u>

### As-Fabricated Condition:

- <u>SiC/SiC:</u> *Proportional Limit* **or** *Matrix Cracking Strength > Max Component Stress* **to prevent oxygen ingress into CMC**
- <u>Ox/Ox:</u> *Ultimate Tensile Strength > Max Component Stresses*

### Under Service Conditions:

*Rupture Strength in oxygen > Max Component Stress* **over component design lifetime**

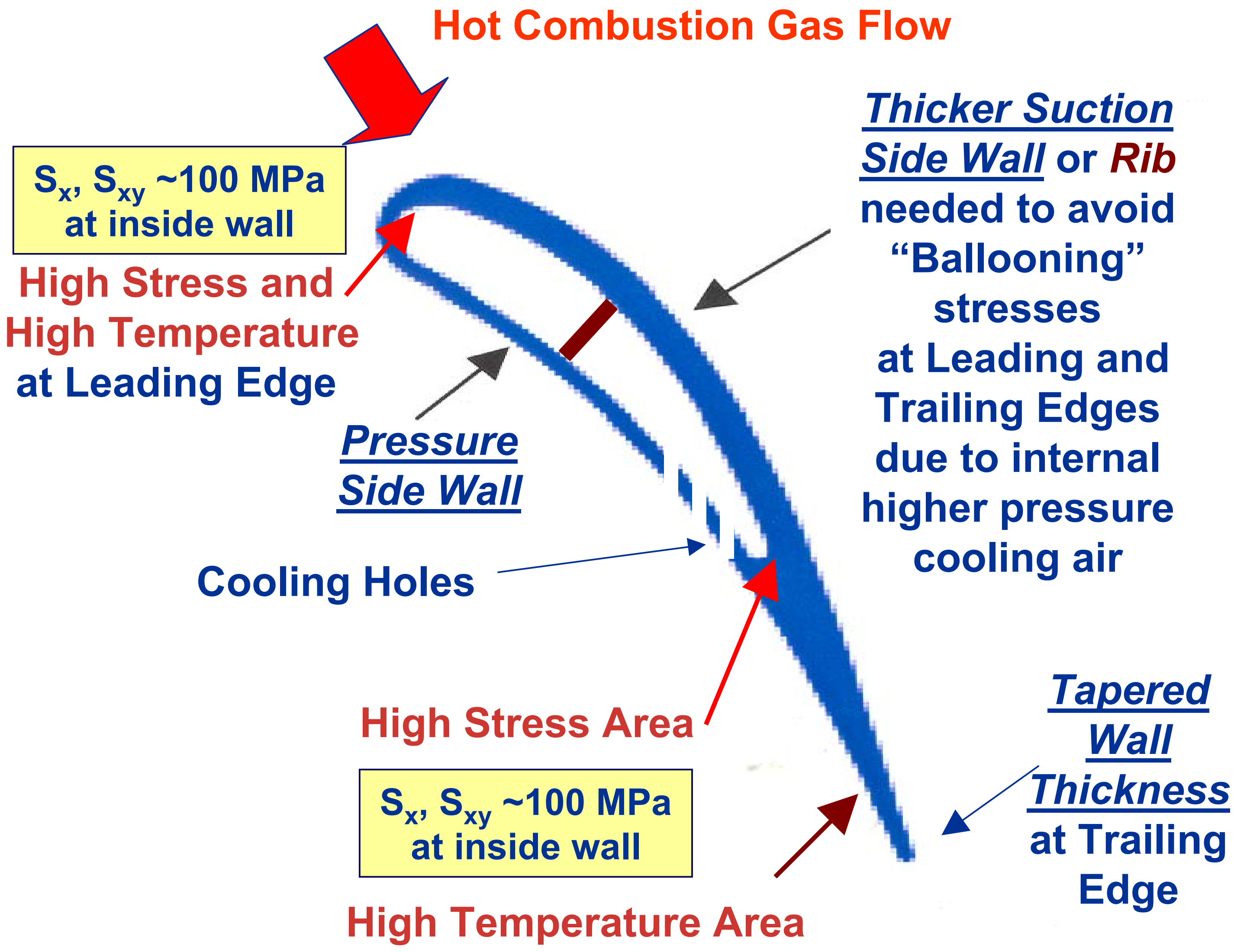
# Typical Maximum Tensile Stresses For Various Hot Section Components

- Limited literature data based on minimally-cooled, thin-walled, dense ***SiC/SiC components*** with 0/90 2D architectures, in-plane elastic moduli of ~250 GPa, and high-temperature $k_z$ of ~15 W/m.K

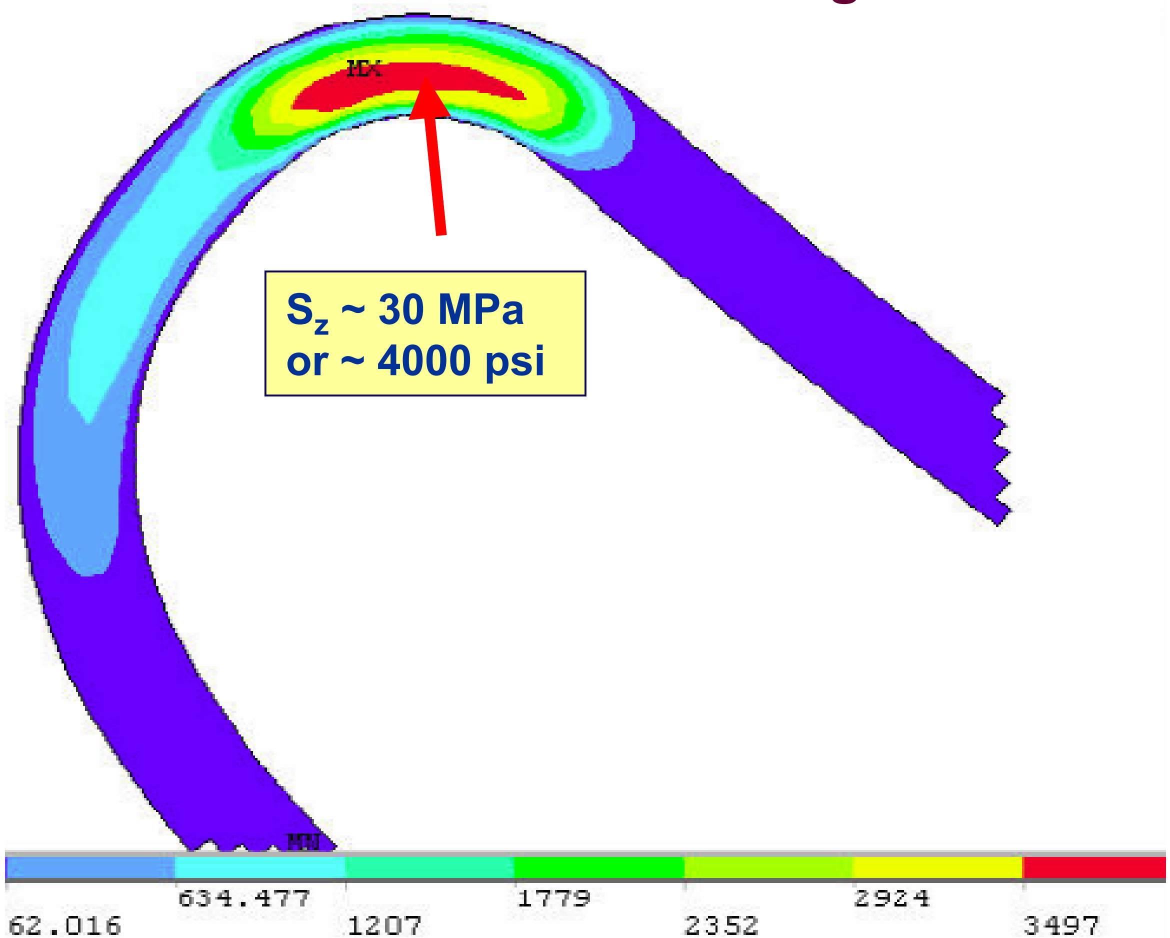
| COMPONENT | MAX STRESS, In-Plane | MAX STRESS, Thru-Thickness | MAX STRESS LOCATIONS |
|---|---|---|---|
| Combustor Liner | ~100 MPa | ~10 MPa | Attachments |
| Turbine Shroud | ~100 MPa | ~10 MPa | Wall at gas inlet |
| Turbine Vane | ~100 MPa | ~30 MPa | Leading, trailing edges |
| Turbine Blade | ~300 MPa | ~30 MPa | Airfoil hot side at root |

***Note: Porous matrix CMC components should have a lower mechanical stress contribution, but a higher thermal stress contribution due to significantly lower conductivity***

# Airfoil Design Requirements Are Complex



# *Thru-Thickness Stress $S_z$ of Particular Concern at Center of Vane Leading Edge Due to Thermal and Ballooning Stresses*




J. Shi et al., UTRC, HT-CMC-5 Presentation, 2004

# As-Fabricated Properties of Some Commercial CMC Systems with 2D Balanced 0/90 Architectures

| | Ox/Ox | SiC/SiNC | SiC/SiC | SiC/SiC |
|---|---|---|---|---|
| *Vendor* | COI Ceramics | COI Ceramics | Goodrich | GE Composites |
| *Name* | N720/AS | S300 | *MI*-HNS | HyPer-Comp |
| *Fiber* | Nextel 720 *(2D fabric)* | Sylramic *(2D fabric)* | Hi-Nicalon-S *(2D fabric)* | Hi-Nicalon *(2D Prepreg)* |
| *Matrix Process* | Sol-Gel Al-silicate *(porous)* | Polymer-derived SiNC *(porous)* | CVI SiC + $(SiC)_p$ + *MI*-Si | $(SiC+C)_p$ + *MI*-Si |
| $S_X$, *MPa* | 195 | 140 | 180 | 167 |
| $S_{XY}$, *MPa* | ~40 | ~60 | ~160 | ~150 |
| $S_Z$, *MPa* | ~3 | ~15 | ~15 | 40 |
| $k_Z$, *W/m K* | 2 | 4 | 28 | 25 |

*Red = not adequate for any component, Blue = adequate for combustor, shroud, Yellow = adequate for combustor, shroud, vane, Green = adequate for any component*

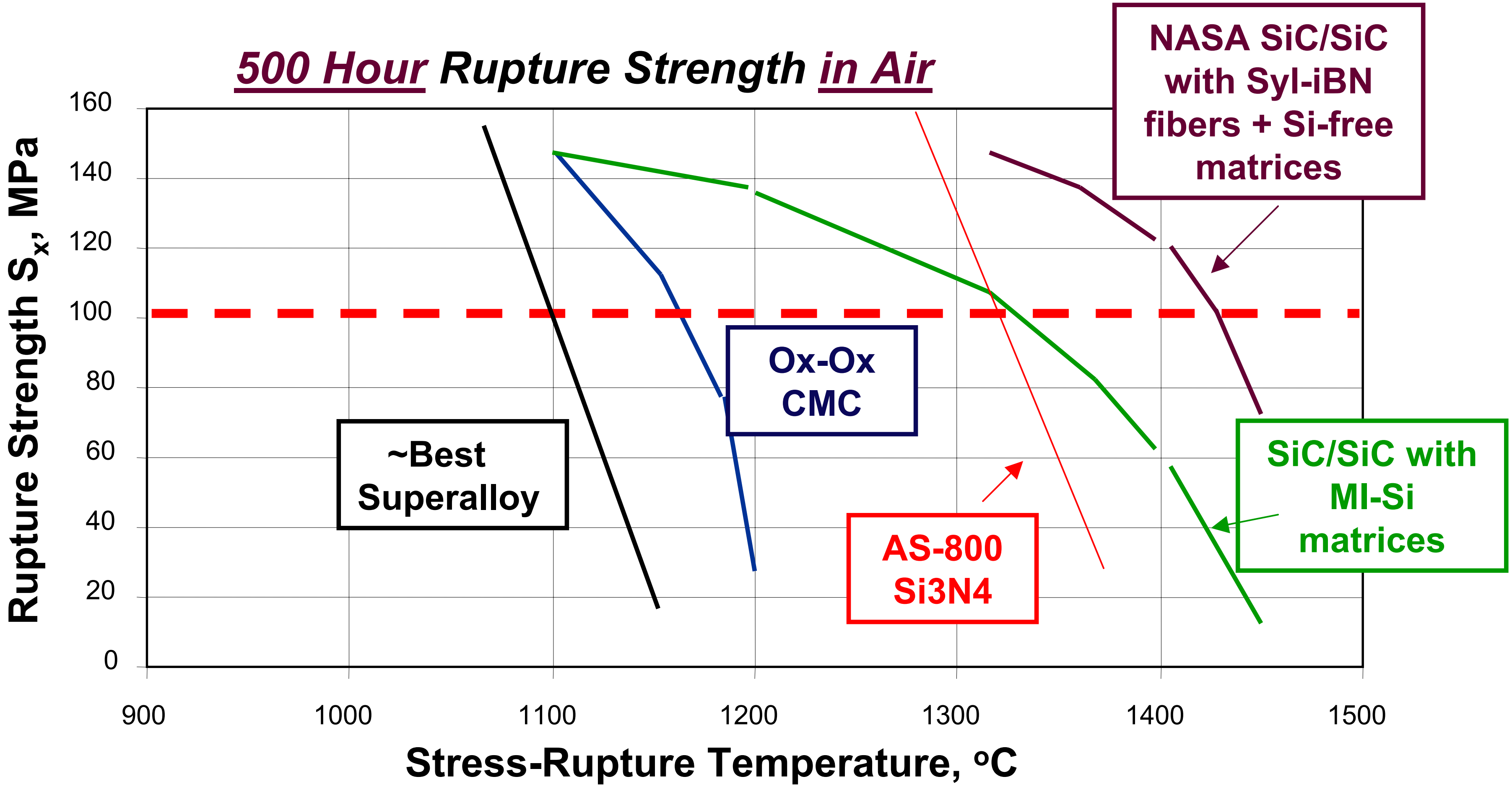
# *As-Fabricated Properties of Some Advanced 2D and 3D SiC/SiC Systems Developed by NASA for Higher Temperature Applications*

Solar Turbines
A Caterpillar Company

| ***Name*** | **N24A** | **N26B** | **N26C** |
|---|---|---|---|
| ***Vendors*** | GE Composites | GE Composites/ Starfire | GE Composites/ Starfire |
| ***Fiber*** | *Sylramic-iBN* | *Sylramic-iBN* | *Sylramic-iBN* |
| ***Architecture*** | 2D *fabric* | 2D *fabric* | *3D woven ply-ply angle interlock* |
| ***Matrix Process*** | CVI SiC + $(SiC)_p$ + *MI*-Si | CVI SiC + *PIP-SiC (Si-free)* | CVI SiC + *PIP-SiC (Si-free)* |
| $S_X$, *MPa* | 180 | 150 | 150 |
| $S_{XY}$, *MPa* | ~200 | ~140 | ~140 |
| $S_Z$, *MPa* | $\boxed{\sim 15}$ | $\boxed{\sim 15}$ | $\boxed{\sim 25}$ |
| $k_Z$, *W/m K* | 25 | 28 | $\boxed{50}$ |

*Red = not adequate for any component, Blue = adequate for combustor, shroud, Yellow = adequate for combustor, shroud, vane, Green = adequate for any component*

# *In-Plane Rupture Strength $S_x$ of Current 2D and 3D CMC Systems*




***Time-Temperature Structural Capability for NASA-developed SiC/SiC systems are higher than superalloys and some of the best monolithics***

# *Summary of CMC Property Status for Hot-Section Components*

- All CMC systems can be competitive with the best superalloys that have densities ~3 times greater.
- The ***SiC/SiC systems with high performance fibers*** are capable of outperforming the best superalloys and Ox/Ox systems in structural capability, upper use temperature, and thru-thickness thermal conductivity. However, these systems currently display ***insufficient strength for blade*** components at all temperatures.
- Although 2D-fabric systems offer simplicity in fabrication, ***2D prepreg and 3D preform systems*** will probably be needed for those components such as ***vanes*** with high ***thru-thickness strength requirements***.
- If the proper SiC fibers are selected, such as Sylramic-iBN, 3D systems should not only provide improved thru-thickness strength, but also ***improved thru-thickness thermal conductivity***, with little loss in in-plane properties.

# *CMC Implementation Issues for Hot-Section Components*

## Environmental Durability

- Water vapor in combustion gas causes surface recession of CMC
  - Recession rate increases with water vapor content, total pressure, combustion gas velocity, and surface temperature
  - Below ~1500°C, Ox/Ox recess slower than SiC/SiC under the same combustion conditions
- ***Environmental Barrier Coatings (EBC*)** with multi-layers of various compositions have been developed and demonstrated for SiC/SiC CMC combustor liners at temperatures to ~1300°C
- ***However little experience exists for using EBC for more complex components operating under more aggressive engine conditions***

# *CMC Implementation Issues for Hot-Section Components*

## Shape Producibility

- 2D and/or 3D fiber architectures for CMC hot-section components must not only provide structural properties required at practically all locations in component, but also meet the component shape requirements.
- ***Currently for complex-shaped CMC components such as vanes and blades, it is practically impossible for any single architecture to simultaneously achieve all structural and shape requirements***
- Some key areas of concern include ***bending and residual stresses in high-performance high-modulus fibers***, and architectures that can simultaneously provide ***smooth component surfaces, T-sections at internal ribs, and thin trailing edges.***

# *CMC Implementation Issues for Hot-Section Components*

## Design Methodologies

- For CMC to be reliably implemented in hot-section components, there has to exist design and lifing data bases for selection of constituent materials, processes, and architectures that will yield components with directional strength properties safely below predicted component stress states at the end of the desired component service life.
- ***These needs have been difficult to address due to such issues as the high cost for obtaining design and lifing data bases, the problems in matching the architectural requirements for structural properties with those for component shape requirements, and <u>current lack of robust modeling approaches for converting the numerous CMC lifing mechanisms into Finite Element codes</u>.***

# *CMC Implementation Issues for Hot-Section Components*

## Affordability

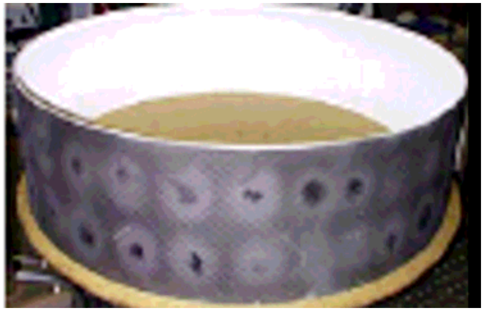
- Ox/Ox components are less expensive than SiC/SiC due to lower cost constituents and processes, but ***lack of significantly higher performance over superalloys is a current barrier to acceptance.***

- ***Cost for SiC/SiC components is still a major issue:***
  - High cost for high performance SiC fiber
  - Constituent, composite, and EBC vendors are often different and single organizations, complicating production time, availability, and resulting in multi-tiers of profit taking
  - Considerable hand-labor required for complex shapes
  - Process technologies are continually being optimized
  - Quality control at every process step is costly
  - Reliable life-cycle cost-benefit analyses need to be conducted to determine economic viability

# Recent Successes for Ox/Ox and SiC/SiC Combustor Liners

- Solar Turbines Inc. has incorporated a very simple combustor design in which ***CMC annular combustor liners*** are functioning as cylindrical hot walls inside a metallic casing with stress levels below the limits at which the CMC strength would be of concern.

- N720/AS Ox/Ox liners have operated >20,000 hrs due to a ~4 mm thick Friable Graded Insulation (FGI) on the liner, keeping liners below 1000ºC. The FGI concept was conceived by Siemens Westinghouse Power Corp. (SWPC), and further developed by SWPC, COI Ceramics, and Solar.



**Ox/Ox with FGI**

- Two sets of slurry-cast Hi-Nicalon / MI-SiC liners with EBC coatings have accumulated >15,000 hrs and 92 starts (2000-2002) and ~14,000 hrs and 61 starts (1999-2000), respectively.

**SiC/SiC**

# *Recent Success for SiC/SiC Turbine Shrouds*

- GE Energy has successfully evaluated ***SiC/SiC gas turbine shrouds*** for its 7FA advanced gas turbine (~170 MW in combined cycle).

- In a test engine, 9 out of 96 first stage inner shrouds were replaced with EBC-coated SiC/SiC shrouds fabricated with the GE Hi-Nicalon prepreg and slurry-cast MI CMC systems.

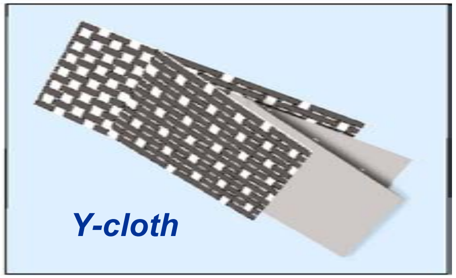

- Shrouds were tested for >5000 hrs and >10 start-stop cycles at material temperatures up to ~1250ºC. Localized EBC spallation was observed, but no appreciable degradation of the CMC mechanical properties was observed.

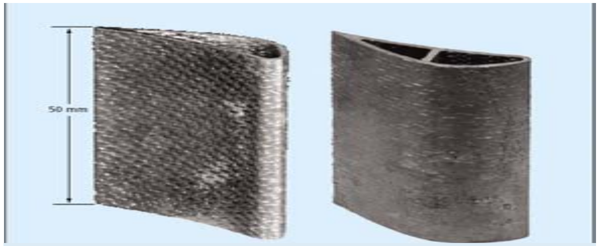
# Recent Successes for SiC/SiC Vanes

United Technologies Research Center and NASA Glenn have recently demonstrated slurry-cast Sylramic-iBN / MI-SiC *turbine vanes* that are compatible with turbine rotor inlet temperatures ≥ 1650ºC with 15-25% reduced cooling.

- **UTRC incorporated an impingement-cooled EBC-coated CMC shell over a metal spar that was satisfactorily tested in a burner rig for 6 hours at a maximum CMC temperature of 1316ºC, followed by 100 thermal cycles (2 min) between 1316ºC and 482ºC.**

- **NASA focused on convectively-cooled center airfoil sections with a sharp trailing edge achieved with an innovative 2D cloth configuration (Y-cloth). Testing in NASA's High Pressure Burner Rig (HPBR) at 6 atm consisted of 50 hrs of successful steady state operation and 102 thermal cycles (2 min.), with gas temperatures from 900-1050ºC (minimum) to 940-1440ºC (max).**




*NASA Prototype Vanes without and with Single Rib*

# *Outlook for CMC Hot Section Components*

- CMC hot-section components will continue to be considered for a variety of engine markets due to their capability to outperform monolithic ceramics in damage tolerance and metallic superalloys in upper use temperature and reduced weight.
- Commercialization of CMC technology within the next 5 to 10 years is likely for medium to large-sized components that are thin-walled and relatively simple in shape (combustor liners, transition pieces, seal rings, shrouds, etc.).
- For more complex-shaped components, key technical and economical hurdles will need to be overcome:
  - size limitations associated with fiber tow sizes and preforms
  - difficulty of high performance fibers to accommodate sharp radii of curvature,
  - use of matrix infiltration processes which limit part thickness,
  - complex cost issues to achieve and demonstrate component performance under real engine conditions.

# *Acknowledgements*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